Water Science and Engineering 2019, 12(3): 221–234

HOSTED BY ELSEVIER

Available online at www.sciencedirect.com

Water Science and Engineering

journal homepage: http://www.waterjournal.cn

Morphodynamics of sandy beaches under the influence of storm sequences: Current research status and future needs

Sonja Eichentopf [a,*], Harshinie Karunarathna [b], José M. Alsina [c]

[a] Department of Civil and Environmental Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[b] College of Engineering, Swansea University, Bay Campus, Swansea SA1 8EN, UK
[c] Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya, Barcelona 08034, Spain

Received 18 February 2019; accepted 23 July 2019
Available online 12 September 2019

Abstract

This paper reviews and discusses the current research status, trends, and future needs in the field of beach morphodynamics under the influence of storm sequences. The paper reviews how the three main research methods, field investigations, numerical modelling, and physical modelling, have been used to study beach morphodynamics during storm sequences. Available quantitative definitions of storm sequences at different sites are presented and discussed. It is shown that the definition of storm sequences is site-specific and requires knowledge of the storm climate, beach characteristics, and the temporal scale of beach recovery. Subsequently, the paper brings together currently available approaches aimed at describing the effect of storm sequences on beach erosion in a general way. The importance of storm chronology and the effects of an extreme storm within a sequence of storms are highlighted. Following that, the more poorly studied aspect of beach recovery in between storms within a sequence is discussed. Three indicators for defining beach recovery, namely the shoreline location, sediment volumes, and the beach state, are identified and compared. Finally, important research needs, including the need for detailed physical modelling, are identified.

Keywords: Storm sequences; Beach morphodynamics; Beach erosion; Extreme storms; Return period; Beach recovery

1. Introduction

Storms that occur in close temporal succession (called *storm sequences*, *storm groups*, *storm clusters*, or *merged events*) have often been regarded to present a high, yet underestimated, risk for natural environments and human activities at the coast. A storm that occurs within a sequence may lead to unexpectedly severe beach erosion because the beach does not have time to recover from a previous event before the storm makes landfall (e.g., Cox and Pirrello, 2001; Ferreira, 2005; Karunarathna et al., 2014a). Recently, Sénéchal et al. (2017) reported that beach erosion under storm sequences is generally larger than the cumulative erosion caused by the storms within the sequence. Other studies suggest that the beach evolves towards equilibrium without a cumulative effect of storm sequences where beach erosion only continues if previous wave energy levels are exceeded (Yates et al., 2009; Vousdoukas et al., 2012; Coco et al., 2014). Consequently, the effects of storm sequences on beaches are not clear but rather complex, which is also related to the numerous interrelated influencing factors (e.g., number of storms, storm chronology, wave conditions, beach states, storm duration, and interval between storms), calling for further scientific studies.

Traditionally, research on coastal morphodynamics has focused on the impacts of isolated storm events and their consequent erosion potential on beaches by analysing the data

This work was supported by the EPSRC FloodMEMORY Project (Grant No. EP/K013513/1) and the HYDRALAB^{+} Integrated Infrastructure Initiative, RESIST (Contract No. 654110), Horizon 2020, European Community.

* Corresponding author.
E-mail address: sonja.eichentopf16@imperial.ac.uk (Sonja Eichentopf).
Peer review under responsibility of Hohai University.

https://doi.org/10.1016/j.wse.2019.09.007
1674-2370/

acquired by three methodologies: field measurements (e.g., Morton, 1976; Birkemeier, 1979), numerical simulations (e.g., van Rijn et al., 2011), and physical modelling (e.g., Shimizu and Ikeno, 1996; Dette et al., 2002). In comparison to beach erosion due to storms, subsequent beach recovery is less studied. Also, in studies on storm sequencing (e.g., Pender and Karunarathna, 2013), beach recovery is often neglected (e.g., Cox and Pirrello, 2001; Ferreira, 2005; Splinter et al., 2014; Dissanayake et al., 2015a, 2015b). For storm sequences, beach recovery processes are, however, of particular importance because insufficient recovery within a sequence is a major reason for potentially increased beach vulnerability.

In the early stage of this research field, a limited number of studies has addressed the importance of storm sequences for beach morphodynamics (e.g., Thom and Bowman, 1980; Morton et al., 1995; Lee et al., 1998; Birkemeier et al., 1999; Cox and Pirrello, 2001; Morton, 2002; van Enckevort and Ruessink, 2003). In their early work, Thom and Bowman (1980) were one of the first to associate severe beach erosion observed in 1973 and 1974, at the coast of New South Wales, Australia, to the occurrence of storm sequences. Morton et al. (1995) focused on the impact of extreme single storms acting on the Texas Gulf Coast, USA. They reported that, due to insufficient recovery between two major storms in the 1980s, the total erosion caused by the two events was larger than the cumulative erosion expected by the storms as single events. Using a sediment budget analysis, Lee et al. (1998) and Birkemeier et al. (1999) found that at Duck, North Carolina, USA, storm sequences generated larger morphological changes than isolated storms. Cox and Pirrello (2001) showed that, in a given period of time, a statistically expected number of weak storms can generate far more erosion than a single extreme event that would (statistically) occur only once in the same period of time. Morton (2002) reported that both increased morphological changes and no cumulative effect of storm sequences have been observed in historical storm events. van Enckevort and Ruessink (2003) used video observations to study bar migration rates on different timescales at Noorwijk, the Netherlands. They found that bar migration rates are determined by sequences of high energy events rather than by individual events.

Only recently, the investigation of the effects of storm sequences on beaches has received increasing attention. This is expressed by an increasing number of research projects dedicated to the investigation of the effects of storm sequences on beaches, for instance in Europe (e.g., Karunarathna et al., 2014b; Eichentopf et al., 2019) and Australia (e.g., Woodroffe et al., 2012; Nichol et al., 2016). The increasing research interest in storm sequences is clearly motivated by the growing awareness of the coastal risks induced by more frequent and/or more intense storms in the context of climate change as derived from global climate simulations (e.g., Webster et al., 2005; Knutson et al., 2010; Bender et al., 2010) and palaeorecords (e.g., Nott and Hayne, 2001; Hurst et al., 2016). For example, the winter of 2013 to 2014 was a recent period of exceptional storm activity at the North-West Atlantic European coasts. Severe erosion and damage in the UK and France due to an extraordinarily high storm frequency and limited post-storm recovery time were reported (Masselink et al., 2016a, 2016b). Recently, Reguero et al. (2019) reported an increase of 0.4% in global wave power due to oceanic warming with potential influence on storm frequency and coastal processes. This highlights the need to study the effects of storm sequences in a climate change scenario.

Because of the increasing awareness of the relevance of storm sequencing under a changing climate and the possible effects on beach evolution, it is of interest to review the current research status, to bring together the existing study approaches, and to identify research gaps that can be of interest for future research. This work focuses on the response of sandy beaches to storm sequences. It is noted that, depending on the sediment type, beaches exhibit different responses, as it was extensively studied for gravel beaches in the BARDEX experiments (e.g., Williams et al., 2009, 2012; Masselink et al., 2016c) and as it is known from earlier experiments (e.g., Kraus and Larson, 1988).

This article is organised as follows: Section 2 presents the qualitative definition of storm sequences and ways to quantify the forcing of storm sequences. In section 3 we show the current research status to study beach morphodynamics under storm sequences based on data from field measurements, numerical modelling, and physical modelling. From this current research status, attempts for general descriptions of the effects of storm sequences on beach morphodynamics are presented in section 4. Section 5 describes how beach recovery can be defined and it is shown that different beach recovery definitions can result in highly different recovery times. Based on the results from the previous sections, important future research needs are derived in section 6 and conclusions follow in section 7.

2. Definition of storm sequences and their destructive forcing

In this section, firstly, the qualitative definition of storm sequences is presented. Secondly, it is shown how the destructive forcing of storm sequences has been quantified in previous studies.

2.1. Definition of storm sequences

In this section the important qualitative definition of storms and storm sequences is resumed. This definition is essential for studies on storm sequencing and beach change and, hence, can be found in many works related to the research field (e.g., Ferreira, 2005; Karunarathna et al., 2014a; Splinter et al., 2014; Sénéchal et al., 2017).

The qualitative definition of storm sequences with important parameters is illustrated in Fig. 1. To identify a storm sequence from wave records, firstly, threshold wave conditions (usually a threshold wave height $H_{s,threshold}$) of a storm are defined (dashed line in Fig. 1) and waves above the pre-selected threshold are taken as storm waves. This approach is well-known as the peak-over-threshold (POT) method

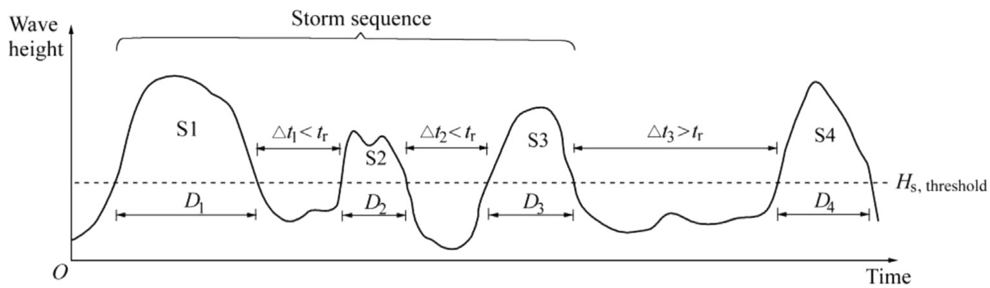

Fig. 1. Qualitative definition of a storm sequence and important parameters.

(Goda, 2010). In a few studies, a minimum duration of these wave conditions is also defined (e.g., 1 hour in Karunarathna et al. (2014a); Dissanayake et al. (2015a)). Some authors also define a minimum time between the storms (e.g., 12 hours in Dissanayake et al. (2015a)) to count them as separate events and not as a single event. Harley (2017) calls this minimum time between storms the "meteorological independence criterion" in his work on the definition of coastal storms.

In order to define a storm sequence, secondly, a maximum time interval between storms which is less than the system recovery time (t_r in Fig. 1) is defined (see section 5 for details on recovery indicators and times). In Fig. 1, the first three storms (S1, S2, and S3) form a storm sequence because the time interval Δt between the storms is less than the time required for recovery under the given wave conditions. The fourth storm (S4) does not count as a member of the storm sequence because of sufficient recovery time after S3. The definition of recovery is site-specific and depends on how slowly or rapidly a beach can recover after a storm (see also section 5). D_1, D_2, D_3, and D_4 indicate the duration of the storms as the time interval during which the threshold wave height is exceeded.

In several studies, it can be observed that the threshold parameters of a storm are not very rigid. For instance, Vousdoukas et al. (2012) counted one event as a storm that resulted in considerable beach profile change even though the pre-defined storm wave height threshold was not reached. Similarly, Coco et al. (2014) considered one event as a storm that did not exceed the threshold wave height but lasted for a long time compared to the other events in the sequence and, hence, generated important erosion. Also, Loureiro et al. (2012) reported that in the identified storm sequences not every storm event exceeded the storm threshold wave height. It becomes evident that the impact of a storm on the beach is often used as a decisive factor to define a storm. This is in line with Ferreira (2005), who defined a storm wave height threshold based on severe erosion of the beach. However, the impacts of storms are difficult to predict (especially if they occur within a sequence) and, hence, storms approaching the coast cannot be well defined based on their future impact. For the definition of storms and storm sequences from wave records and beach profile data, it is important to note that the definitions are highly site-specific and subjective as it will be shown in sections 3.2 and 5.

2.2. Quantification of the destructive forcing of storm sequences

Two main parameters have been used in the context of storm sequences to assess the destructive forcing of individual storms and of a whole sequence. These parameters are the storm power index P (e.g., Karunarathna et al., 2014a; Dissanayake et al., 2015a; Angnuureng et al., 2017) and the integrated wave power (e.g., Splinter et al., 2014). Originally, these parameters were introduced for single storms and were later applied for storm sequences.

The *relative storm power* or *storm power index* was defined by Dolan and Davis (1992, 1994) based on the maximum deep-water significant wave height $H_{s,max}$ (m) and the duration D (h) of a storm as follows:

$$P = H_{s,max}^2 D \tag{1}$$

Based on $H_{s,max}$, D, and P, Dolan and Davis (1992, 1994) defined five storm classes and qualitatively described the coastal impacts of these storms in terms of beach erosion, overwash, and property damage. P accounts for two important factors determining the strength of a storm because the higher $H_{s,max}$ and D, the higher P and the more severe the assumed damage to a beach (Karunarathna et al., 2014a). Further definitions for storm severity which solely account for the peak storm wave height exist, such as the storm severity index by You and Lord (2008). This shows that the wave height is generally recognised as one of the most crucial parameters for the definition of storm severity. However, these parameters do not account for the obliquity of the storm waves to the shoreline and the longshore gradient of wave power distributed along the coast.

Karunarathna et al. (2014a) used the storm power index as an indicator for the erosion potential of individual storm events and storm sequences acting on Narrabeen Beach, Australia. The total storm power index of a whole sequence was computed as the sum of the power index of all storms in the sequence. The eroded beach volume at Narrabeen Beach (between 10 m above and 2 m below mean water level) was found to linearly depend on the storm power index for both individual storms and storm sequences with stronger erosion in the case of storm sequences (larger gradient of linear fit for storm sequences (see Figs. 8 and 11 in Karunarathna et al. (2014a)). Despite the limited number of data points in the figures, the results show that the power index correlates well with erosion volumes caused by both individual storms and storm sequences at Narrabeen Beach.

P was modified by Dissanayake et al. (2015a) to account for the wave height variation during a storm (Eq. (2)).

$$P_{\mathrm{mod}} = \sum_{i=1}^{n} H_{\mathrm{s},i}^2 D_i \tag{2}$$

where the time series is divided into n sub-segments, and $H_{\mathrm{s},i}$ and D_i are the deep-water significant wave height and the associated duration in each of the sub-segments, respectively.

P_{mod} avoids overestimation of the storm effect that results from computing P based on the maximum significant wave height of the whole storm. Dissanayake et al. (2015a) found that the change of the multi-barred part of the beach at Sefton Coast depended (at least qualitatively) on P of a storm. A storm with a higher P resulted in a flatter beach profile. Angnuureng et al. (2017) also used the power index as a proxy for storm power. They followed a similar approach to that of Dissanayake et al. (2015a), integrating the time-dependent significant wave height of the storm over time.

P presents a simple descriptor that accounts for two important factors to determine storm power. However, because Dolan and Davis (1992) did not obtain the wave period from the data, their definition does not account for the wave period during the storm. Splinter et al. (2014) computed the integrated wave power P_{s} based on deep water significant wave height H_{s} (m), the peak wave period T_{p} (s), and the storm duration D (h) as follows:

$$P_{\mathrm{s}} = \int_0^D \frac{\rho g^2}{64\pi} H_{\mathrm{s}}^2 T_{\mathrm{p}} \mathrm{d}t \tag{3}$$

where ρ (kg/m^3) is the sea water density, g (m/s^2) is the gravitational acceleration, and t (s) is time.

In earlier studies, Lee et al. (1998) and Birkemeier et al. (1999) also used storm power as a measure of storm intensity obtained by integrating the wave power over the storm duration. Splinter et al. (2014) showed that both the cumulative wave power and the cumulative wave energy, which does not account for the wave period, were similarly related to the eroded dry beach volume, indicating that the wave period was not significant for the beach erosion in the studied data set.

3. Investigation of storm sequence effects using data from field measurements, numerical modelling, and physical modelling

Beach evolution under varying hydrodynamic forcing can be studied using field data, numerical modelling, and physical modelling. These methods are often combined in order to improve measuring and modelling techniques or to obtain more detailed insights into the occurring processes. Fig. 2 shows major links between the methodologies.

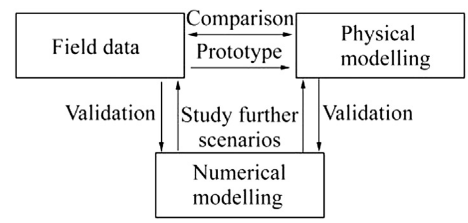

Fig. 2. Study methodologies and their major links.

All three methods are well-established for the investigation of the effects of individual storms on beaches and can be adapted for the study of storm sequences. Major requirements for this adaptation are (among other aspects): (1) a solid definition for the identification of storm sequences for a specific site, (2) numerical models that are capable of accurately modelling beach recovery during calm periods in between storms along with sufficient computational resources, and (3) increased resources (available facilities, time, and capital) for the performance of long series of high-mild energy wave conditions in physical experiments.

In this section, firstly, the main factors that influence beach vulnerability under changing wave conditions are presented. Secondly, it is reviewed to what extent data from field measurements, numerical modelling, and physical modelling have been used to study the effects of storm sequences on beaches, and strengths and weaknesses of the three methods are discussed. This section focuses on studies that investigated storm sequencing and beach response using the different methodologies.

3.1. Factors influencing beach vulnerability

Fig. 3 shows factors that have the potential to influence the resilience/vulnerability of beaches during storms and storm sequences.

Coco et al. (2014) defined beach vulnerability as the "potential of a beach to be affected by a major storm" and stated that both storm frequency and recovery rates are crucial for beach vulnerability. Karunarathna et al. (2014a) mentioned the importance of the incident wave conditions, such as wave height, wave period, and wave direction. The relevance of wave period and wave direction has been particularly highlighted in the recent studies of Masselink et al. (2016b) and Mortlock et al. (2017), respectively. Masselink et al. (2016b)

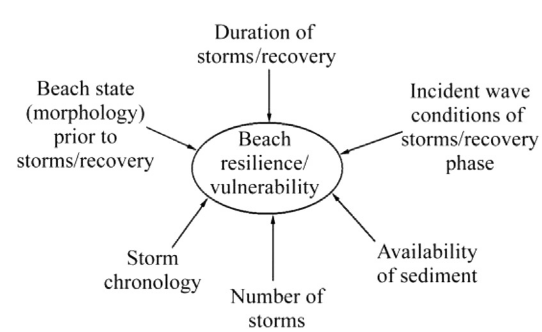

Fig. 3. Major factors influencing beach resilience/beach vulnerability.

reported that a storm with a not unusual wave height but an exceptionally long wave period had an important impact on the coast of Cornwall, UK, during the 2013–2014 winter storms. Mortlock et al. (2017) found that a storm at the Australian East Coast with an unusual wave direction generated some of the most severe beach erosion in 40 years. A further important influencing factor is the storm duration as reported by, for instance, Dolan and Davis (1992), Karunarathna et al. (2014a), and Dissanayake et al. (2015a). The antecedent beach state has also been identified from physical experiments (e.g., Grasso et al., 2009; Baldock et al., 2017) and from field data (e.g., Lee et al., 1998; Birkemeier et al., 1999; Yates et al., 2009; Vousdoukas et al., 2012; Davidson et al., 2013; Splinter et al., 2014; Scott et al., 2016; Morales-Márquez et al., 2018) to influence beach profile evolution under varying wave conditions.

Influencing factors that are specifically relevant to storm sequence effects on beaches are the number of storms in a sequence (e.g., Karunarathna et al., 2014a; Dissanayake et al., 2015b), the chronology of the storms (e.g., Splinter et al., 2014; Dissanayake et al., 2015c), and the time interval between storms in a storm sequence (e.g., Pender and Karunarathna, 2013). The availability of sediment within the morphodynamic system is also fundamental for the ability of a beach to erode or to recover. The sediment availability for recovery periods might depend on the sediment distribution caused by the preceding storm, which can precondition a sediment compartment for recovery (Scott et al., 2016; Dodet et al., 2019).

In addition to the abovementioned factors, further site-specific aspects have to be taken into account. These are particular geometries, including beach slopes and coastline geometry (e.g., Dissanayake et al., 2015a, 2015b), water levels (tide and surge) (e.g., Vousdoukas et al., 2012; Karunarathna et al., 2014a; Coco et al., 2014; Dissanayake et al., 2015b; Angnuureng et al., 2017), and the relative contribution of cross-shore versus longshore sediment transport (Lee et al., 1998; Dodet et al., 2019).

The influence of the abovementioned factors can be investigated using different indicators. These indicators are used to characterise beach profile change and are primarily the sediment budget of the subaerial beach and of the shoreface (surf and nearshore zone) (e.g., Lee et al., 1998; Vousdoukas et al., 2012; Splinter et al., 2014; Coco et al., 2014; Karunarathna et al., 2014a; Dissanayake et al., 2015b; Morales-Márquez et al., 2018; Biausque and Senechal, 2019), the beach width, which is directly related to the shoreline position (e.g., Karunarathna et al., 2014a; Angnuureng et al., 2017; Phillips et al., 2017), and bar response (e.g., Vousdoukas et al., 2012; Coco et al., 2014; Gravois et al., 2016). The choice of the indicator often depends on the purpose of the undertaken work (such as scientific, engineering, or management), the type of beach, the available data, as well as the timescale of the study.

3.2. Field data

Data from regular field measurements of beach profiles and hydrodynamics from coasts in the USA, Europe, and Australia have been used to investigate the influence of storm sequences on beach evolution under natural conditions. Field measurement techniques are not a focus of the present work and the reader is referred to Sénéchal et al. (2017) for more details.

In this section, we present the quantitative definitions of storm sequences that are available for different sites. The data sets and their definitions, including thresholds for storm wave heights and recovery times, are listed in Table 1. Note that the

Table 1
Studied field data sets and their definitions of storms and storm sequences.

Study site	Storm wave height	Storm duration	Maximum time interval between storms	Study period	Reference(s)
Duck, North Carolina, Field Research Facility, USA	$H_s > 4$ m			ca. 10 years (1981–1991)	Lee et al. (1998)
Duck, North Carolina, Field Research Facility, USA	$H_{rms} > 3.15$ m ($H_s > 4.45$ m)	> 12 hours	< 40 days	ca. 18 years (1981–1998)	Birkemeier et al. (1999)
Northwest Portuguese Coast	$H_s > 6$ m		< 21 days between storm peaks; < 14 days between end and start of storms	ca. 12 years (1981–1992)	Ferreira (2002, 2005)
Narrabeen Beach, New South Wales, Australia	$H_s > 3$ m	> 1 hour	< 9 days	ca. 20 years (1981–2000)	Karunarathna et al. (2014a)
Biscarrosse Beach, Southwest France	$H_s > 3.68$ m	> 12 hours	< 10 days	6 years (2007–2012)	Angnuureng et al. (2017)
Faro Beach, South Portugal	$H_s > 3$ m		< 30 hours	21 days (2009–2010)	Vousdoukas et al. (2012)
Truc Vert Beach, Atlantic Coast, France	$H_s > 4.1$ m, $T_p > 10.1$ s			ca. 1 month (2008)	Coco et al. (2014)
Sefton Coast, Liverpool Bay, UK	$H_s > 2.5$ m	> 1 hour	> 12 hours; < 1 month	ca. 2 months (2013–2014)	Dissanayake et al. (2015a, 2015b, 2015c)
Cala Millor, Northeast Coast of Mallorca, Spain	$H_s > 1$ m	> 6 hours	Between 1 and 3 days	ca. 2 weeks (2014)	Morales-Márquez et al. (2018)
Gold Coast, Queensland, Australia	$H_s > 2$ m		Between a few days to less than 2 months	ca. 6 months (1967)	Splinter et al. (2014)
Southwest Portugal	$H_s > 5$ m			2 years (2007–2009)	Loureiro et al. (2012)

Note: H_{rms} denotes the deep-water root-mean-square wave height.

table only contains studies with a quantitative definition of storm sequences. For instance, Castelle et al. (2007, 2008) studied the impact of a storm sequence at Broadbeach, Gold Coast, Australia, but no general quantification of storm sequences was presented and, hence, it is not listed here. Note that the study by Birkemeier et al. (1999) presents an extension of the work by Lee et al. (1998) using an extended time period and a modified storm definition (see Table 1). The storm definition applied by Karunarathna et al. (2014a) originates from Lord and Kulmar (2000) and Kulmar et al. (2005, 2013), who extensively presented the collection of wave data along the coast of New South Wales, Australia.

As becomes evident from Table 1, quantitative definitions of storm sequences have been established for the following three major geographical regions:

(1) the Australian East Coast (Narrabeen Beach (Karunarathna et al., 2014a) and the Gold Coast (Splinter et al., 2014));

(2) the European West Coast/European Atlantic Coast (three sites in Portugal (Ferreira, 2005; Vousdoukas et al., 2012; Loureiro et al., 2012), two sites in France (Coco et al., 2014; Angnuureng et al., 2017), and one site in the UK (Dissanayake et al., 2015a, 2015b, 2015c);

(3) the East Coast of the US/US Atlantic Coast (Duck, North Carolina (Lee et al., 1998; Birkemeier et al., 1999)).

The data sets in Table 1 cover a wide variety of wave regimes (as reflected by the different storm wave height thresholds) and tidal ranges. Most of the studied data sets were obtained in a micro-tidal environment (Lee et al., 1998; Birkemeier et al., 1999; Karunarathna et al., 2014a; Splinter et al., 2014; Morales-Márquez et al., 2018), a few in meso- and macro-tidal environments (Loureiro et al., 2012; Coco et al., 2014; Angnuureng et al., 2017), and Sefton Coast presents a hyper-tidal environment with a tidal range of up to 8.2 m (Dissanayake et al., 2015a, 2015b, 2015c).

Study durations of the data sets presented in Table 1 span periods between three weeks and 20 years, allowing an investigation of the influence of storm sequences on beach evolution on different temporal scales. Observation periods of several years to decades (in Table 1, Lee et al. (1998), Birkemeier et al. (1999), Ferreira (2002, 2005), Karunarathna et al. (2014a), and Angnuureng et al. (2017)) comprise several storm sequences, which can be used for a more general comparison of the influence of storm sequences compared to individual storms and provide insights into medium- to long-term effects of storm sequences with inter-annual changes. For the purpose of the present review, we define data sets that cover at least six years as long-term because they have been used to study the influence of several storm sequences on beaches.

The presented long-term data sets give an insight into the frequency of storm sequences at the different sites (Table 2). This frequency strongly varies between sites where Narrabeen Beach appears to be most frequently affected by storm sequences. For Biscarrosse Beach it has to be considered that possibly not all storm sequences were taken into account due to gaps in the data (Angnuureng et al., 2017). Duck, North Carolina experiences storm sequences the least frequently among the presented sites. The deviation in the storm frequency at Duck between Lee et al. (1998) and Birkemeier et al. (1999) indicates an increased number of storm sequences in the additional eight years of data used by Birkemeier et al. (1999), which seems not attributed to the storm sequence definition.

Table 2
Frequencies of storm sequence occurrence at different field sites (study periods are given in Table 1).

Site	No. of sequences	Frequency (sequences/year)	Reference
Duck, North Carolina, USA	4	0.4	Lee et al. (1998)
Duck, North Carolina, USA	10	0.56	Birkemeier et al. (1999)
Northwest Portuguese Coast	15	1.25	Ferreira (2005)
Narrabeen Beach, Australia	80	4	Karunarathna et al. (2014a)
Biscarrosse Beach, Southwest France	13	2.17	Angnuureng et al. (2017)

While long-term data sets allow the evaluation of long-term trends and the performance of statistical analyses, the focus of short-term studies is the investigation of immediate effects of a particular storm sequence on beach evolution. Also, they are frequently used to validate process-based numerical models (see also section 3.3).

Short-term data were presented by Vousdoukas et al. (2012), Loureiro et al. (2012), Coco et al. (2014), Splinter et al. (2014), Dissanayake et al. (2015a, 2015b, 2015c), and Morales-Márquez et al. (2018) (see Table 1). In Coco et al. (2014) and Loureiro et al. (2012), the maximum time interval between storms to count as one storm sequence was not explicitly defined, but the interval between successive storms was very small (usually less than five days in Coco et al. (2014) and less than six days in Loureiro et al. (2012)).

Overall, from Table 1 it becomes evident that the definition of storms and storm sequences is very site-specific. The definition depends on the method and on the specific wave records that are used to identify storms. For instance, Coco et al. (2014) and Angnuureng et al. (2017) studied storm sequence effects at beaches located approximately 50 km away from each other at the Bay of Biscay and used slightly different wave heights to identify a storm. Nevertheless, because the data in Table 1 were obtained at several sites around the world, the table provides useful precedents for future definitions of storm sequences. Beach recovery is usually described in terms of a system recovery time that ideally accounts for the prevalent hydrodynamic recovery conditions. A storm is usually determined based on the wave height, whereas storm duration, wave period, or wave direction is not generally accounted for.

Field data have been the main tool to study beach morphodynamics during storm sequences. They allow the investigation of the influence of storm sequences on the event-scale as well as on the long-term evolution of beaches under natural conditions. As pointed out by Karunarathna et al. (2014a), a major difficulty of using field data is that pre- and post-storm beach profile measurements often do not match the time of the storm occurrence (see also section 3.3). The optimal beach profile data for storm sequence studies are those for which regular and event-driven beach profile measurements were performed (such as in Birkemeier et al. (1999); Loureiro et al. (2012)). However, this is time-consuming and requires high flexibility from the available manpower, although recent studies have shown the use of remote sensing techniques, such as satellite image analysis (Luijendijk et al., 2018; Vos et al., 2019) and LIDAR measurements (Phillips et al., 2019), as well as of crowd-sourced shoreline images (Harley et al., 2019). Moreover, storm durations and storm magnitudes obtained from field measurements are, by their nature, very variable which makes a detailed comparison of the impacts of storms and storm sequences difficult (Lee et al., 1998). Hydrodynamic and beach profile measurements are usually of limited temporal-spatial resolution because profile data, for instance, can practically not be obtained in the submerged part of a beach during storms (Vousdoukas et al., 2012).

3.3. Numerical modelling

Due to their site-specific nature and limited measurement periods, it is difficult to study specific influencing factors of storm sequences on beach evolution only based on field data. Therefore, numerical modelling presents an important tool to complement the analysis of field measurements. Numerical models have been used in a statistical, equilibrium-type or process-based approach for investigating beach evolution during storm sequences.

Statistical models have primarily focused on defining beach erosion return periods rather than the individual effect of a specific storm sequence. For this purpose, long-term beach profile and hydrodynamic data sets are needed. Callaghan et al. (2008) obtained probability density functions and their joint probabilities for relevant parameters including wave height, storm duration, tidal anomalies, wave period, and wave direction. They empirically determined beach erosion volumes applying the storm erosion model by Kriebel and Dean (1993). Pender and Karunarathna (2013) successfully combined Callaghan et al. (2008)'s statistical approach to obtain a time series of storm events and low energy periods with a process-based model (XBeach) to determine beach profile changes at medium-term (annual to decadal) timescales.

Equilibrium-type models have also been used to study beach evolution (e.g., Miller and Dean, 2004; Yates et al., 2009; Davidson et al., 2013) and have recently been shown to be capable of accounting for storm sequence effects (Davidson et al., 2017). Davidson et al. (2017) presented a semi-empirical shoreline-equilibrium model which was able to predict both shoreline recession due to storms and shoreline recovery after the occurrence of extreme storms. They followed the model developed by Davidson et al. (2013) and successfully adopted it to forecast shoreline change during storm sequences at Perranporth, UK, and Narrabeen Beach, Australia.

Process-based models have mainly been used to study the effect of a single (or a few) storm sequence(s) on beach profiles (short-term influence). Although other process-based models can potentially be used to evaluate the storm sequence influence (see van Rijn et al. (2011) for a comparison of different numerical modelling capabilities for single erosive or accretive events), XBeach is specifically designed to model beach erosion during storms (Roelvink et al., 2009) and has been one of the most common models applied for storm sequences.

The main applications of process-based models are:

(1) the comparison of the effect of storm sequences against the effect of isolated storm events using historic (Dissanayake et al., 2015a, 2015b) or future (Dissanayake et al., 2016) storm sequence scenarios;

(2) the investigation of the erosive impact of different storm chronologies (Splinter et al., 2014; Dissanayake et al., 2015c);

(3) the determination of pre- and post-storm beach profiles where profile measurements did not match the storm occurrences (Karunarathna et al., 2014a; Morales-Márquez et al., 2018).

The erosive effects of storms within a sequence and of isolated events have been extensively studied at Sefton Coast, UK (Dissanayake et al., 2015a, 2015b, 2016). The important difference for the simulations is that for isolated events the storms start from the fully recovered beach, whereas in the sequence scenario the storms start from the post-storm morphology of the previous storm (neglecting recovery).

The influence of different storm chronologies within a sequence on beach erosion was also studied using XBeach simulations. Splinter et al. (2014) and Dissanayake et al. (2015c) reported that total beach volume changes caused by one storm sequence were insensitive to the chronology of storms at the Gold Coast, Australia, and at Formby Point, Sefton Coast, UK. On an event-scale level, however, Dissanayake et al. (2015c) identified differences in beach erosion between the storm chronologies. For instance, a storm was found to always generate the largest erosion when it occurred first in a sequence (see Fig. 8 in Dissanayake et al. (2015c)), most likely because the beach had not yet experienced much change. This is in line with observations based on field measurements by Coco et al. (2014), who reported largest erosion during the first storm in a sequence, and by Scott et al. (2016), who stated that the eroded sediment volume is larger when a storm makes landfall on a fully accreted beach.

Karunarathna et al. (2014a) and Morales-Márquez et al. (2018) used XBeach simulations to obtain beach profiles at desired time instants between storms because beach profile measurements did not always match the storm occurrences.

Numerical modelling allows the evaluation of different aspects of storm sequences regarding beach evolution that may not be examinable with field data. For the use of numerical models, beach recovery is frequently neglected, usually because little recovery between the storm events is assumed (Splinter et al., 2014; Dissanayake et al., 2015a, 2015b, 2015c, 2016). Pender and Karunarathna (2013) presented one of the few studies accounting for beach recovery phases in their model. They calibrated XBeach separately against storm and recovery profiles and showed that XBeach is capable of modelling beach recovery by accounting for the governing processes (primarily wave skewness and asymmetry).

It is important to note that models like XBeach require extensive calibration of the model parameters. The resulting performance of the numerical model is essential to the reliability of the predicted beach profile under the influence of storm sequences. van Rijn et al. (2011) used the Brier Skill Score (BSS) (van Rijn et al., 2003) to compare the prediction skill of three numerical models for beach profile evolution under a high energy event followed by a low energy event in physical experiments. The BSS was at least "good" for almost all profiles obtained under high energy conditions but only "fair", "poor", and "bad" for the three profiles under low-energy (recovery) conditions which might be a reason for recovery phases being usually neglected in numerical simulations. For the simulation of a single storm event, the weak performance for recovery phases might not be significant, but it becomes more crucial with increasing numbers of storms and recovery phases where the simulated profile is used as initial profile for a subsequent storm.

3.4. Physical modelling

In addition to the investigation of field measurements and the performance of numerical modelling, physical experiments present a further way to study beach evolution under varying wave conditions. However, despite allowing detailed measurements under controlled conditions, physical modelling is currently the least used approach to studying storm sequences.

Physical modelling has been performed to study beach profile evolution under the influence of a sequence of one high energy event followed by one low energy event. Eichentopf et al. (2018) reviewed available large-scale experimental data sets that comprise high energy followed by low energy conditions. An important outcome was that even for a sequence of single high-low energy conditions the existing data sets are limited (e.g., Kraus et al., 1994; Sánchez-Arcilla et al., 1994; Yoon and Cox, 2010; Cáceres et al., 2008; Cáceres and Sánchez-Arcilla, 2015) (see Table 2 in Eichentopf et al. (2018) for an overview of the facilities and the wave conditions). These high-quality data sets have provided insights into beach profile evolution under different wave conditions. However, they are not sufficient for the investigation of storm sequencing, mainly because they do not account for the influence of previous beach states.

Physical experiments that account for the effect of storm sequences on beach profile change are very scarce. An exception are the medium-scale experiments comprising storm sequences presented by Gravois et al. (2016). They performed experiments on a 1/15 sloped beach profile consisting of two immediately consecutive storm events, i.e., without a recovery time between the two events. To investigate the influence of the chronology of the storms within a sequence, each sequence of two storms was carried out twice, one time as "forward sequence", and for the second time the order of the two storms was reversed ("reversed sequence"). An important finding of their work was that the beach profile that resulted from a highly energetic event was very similar in both cases, regardless of whether it started from the plane beach profile or from the morphology after an antecedent weaker storm.

Compared to field measurements, physical modelling has the advantage of allowing the investigation of beach morphodynamics under controlled and defined conditions. The isolated effects of influencing factors and the cross-shore evolution of the hydrodynamics and the beach profile can be studied without effects of site-specific aspects.

Recently, Eichentopf et al. (2019) presented one of the first large-scale experiments on morphodynamic changes due to storm sequences comprising both storm and recovery conditions. In contrast to small-scale experiments, large-scale experiments have the advantage of being less affected by scaling (Sánchez-Arcilla et al., 2011), and they allow obtaining detailed temporal-spatial measurements of water surface elevation, beach profiles, sediment concentration, and flow velocities. These data are important for investigating more detailed beach profile and hydrodynamic changes as well as sediment transport processes during storm sequences.

4. Towards general descriptions of the erosive effect of storm sequences

General descriptions of the influence of storm sequences on beach evolution are not straightforward from field data, mainly because of the site-specific beach characteristics and the interrelations between different influencing factors. Three approaches are identified from the literature to describe the influence of storm sequences on beach morphodynamics in a general way: (1) the destabilising hypothesis (Birkemeier et al., 1999), (2) the role of an extreme storm within a sequence (e.g., Coco et al., 2014; Gravois et al., 2016), and (3) the concept of a benchmark storm accounting for storm sequences (e.g., Ferreira, 2005; Karunarathna et al., 2014a).

4.1. Destabilising hypothesis

An early suggestion on the influence of storm sequences on beach resilience is the *destabilising hypothesis*. This was initially addressed by Lee et al. (1998) and named by Birkemeier et al. (1999). It states that the early storms within a sequence destabilise the beach. The beach has insufficient time to recover before the next storm arrives and, therefore, more severe beach changes occur during the following storms. This hypothesis was then addressed by further studies (e.g., Ferreira, 2005).

4.2. Effect of a very extreme storm within a sequence

Particular attention has been paid to the most extreme storm within a sequence. Gravois et al. (2016) found in their experimental study that an extreme storm generated the same beach profile regardless of whether it occurred first or second in a sequence of two storms. This shows the large impact of extreme storms and indicates that, for the effect of an extreme storm, the storm chronology is of minor importance. The numerical study by Dissanayake et al. (2015c) supports this finding. Their results showed that the eroded volume of an extreme storm is very similar and almost consistently the largest in the sequence regardless of whether a weaker storm occurred before.

Coco et al. (2014) addressed the particular case where the most extreme storm occurs at the beginning of the sequence. They postulated that, because this first storm causes strong erosion, the following weaker storms have a minor erosive effect. Coco et al. (2014) argued that this is because the beach continuously strives to reach an equilibrium state. If this equilibrium is strongly disrupted by an extreme storm, subsequent storms generate less beach change because the beach tries to reach a new equilibrium. In line with that, the earlier study by Vousdoukas et al. (2012) stated that once a new equilibrium is reached, further beach erosion occurs only if storm intensity and/or water levels are larger compared to previous storms.

Severe erosion during the first storm of a sequence was observed by Dissanayake et al. (2015a, 2015b) during the 2013−2014 winter storms at Formby Point of Sefton Coast, Liverpool Bay, UK, using the numerical model XBeach. However, the findings were inconclusive as a result of the complex nature of this beach and its hyper-tidal environment.

The suggestions regarding the effect of an extreme storm in a sequence (Coco et al., 2014; Dissanayake et al., 2015a, 2015b; Gravois et al., 2016) are not entirely in line with the destabilising hypothesis. Recalling the destabilising hypothesis, it postulates that due to increased beach vulnerability, subsequent storms generate larger beach change than they would generate on the fully recovered beach.

Contrary to the finding of reduced beach erosion after an extreme storm, Castelle et al. (2007, 2008) reported strong erosion during all three storms of a sequence at the Gold Coast, Australia, in 2006. The first storm presented the most extreme event since at least 1976 in terms of its wave height and duration, resulting in severe subaerial beach erosion and offshore migration of the outer bar. During the two following weaker storms, unusually large erosion occurred, which Castelle et al. (2007, 2008) linked to the offshore migrated outer bar providing reduced beach protection. This again shows that all the presented field observations are very site-specific with different tidal ranges, geographic settings, and wave characteristics as presented in section 3.2.

4.3. Benchmark storm accounting for the erosive effect of a storm sequence

For coastal management and planning, traditionally an n-year return period of a specific storm intensity (usually expressed by the wave height) is used as a *benchmark storm* (also referred to as a *design storm*). Hence, it is postulated that a storm with an n-year return period results in an n-year beach erosion which is, even for single storms, a simplification (Callaghan et al., 2009). The approach does not account for storm sequences that may have a large erosive effect due to a concentration of wave energy within a short period of time (Kuriyama and Yanagishima, 2018; Dodet et al., 2019).

To make the approach of a benchmark storm applicable for storm sequences, a storm sequence is considered to act as a large single storm (Lee et al., 1998). In this case, the return period of a single storm that causes the same erosion as the entire storm sequence is used as the benchmark storm (e.g., Birkemeier et al., 1999; Ferreira, 2005, 2006; Karunarathna et al., 2014a).

To define such an *equivalent single storm*, long-term beach profile and wave data are used. Firstly, a relationship between the erosion volume of single storms and their return periods are defined (squares and solid black line in Fig. 4). Secondly, the cumulative erosion of a storm sequence is obtained (sum of eroded volume of each storm within the sequence). Finally, the return period of a single storm that would generate this cumulative erosion volume is defined (examples are qualitatively illustrated as grey and dashed lines in Fig. 4). The return period of this equivalent single storm was found to be very high in previous studies because of the high cumulative power of a storm sequence and its associated large cumulative erosion (Birkemeier et al., 1999; Ferreira, 2005; Karunarathna et al., 2014a).

Ferreira (2005) suggested that the erosion return period approach should replace the traditional wave height return period approach. This erosion benchmark event can account for the effect of storm sequences as explained above. In line with that, Cox and Pirrello (2001) stressed the importance of not simply studying isolated events but incorporating cumulative effects of storms into the benchmark criterion. Callaghan et al. (2008, 2009) also questioned the suitability of wave height benchmark storms and found that their statistical approach, which accounts for the effect of storm sequences, describes beach erosion more accurately for return periods of up to ten years at Narrabeen Beach.

The approach of benchmark storms accounting for storm sequences is of particular interest for engineering purposes because the return period of a single storm can be well used as a rating for the planning and implementation of engineering measures. However, the return period of the *equivalent storms* is usually defined based on the cumulative erosive effect of the storms within a sequence. Recovery phases between storms within a sequence were considered by Pender and Karunarathna (2013) and Karunarathna et al. (2014a) but were usually neglected in other studies.

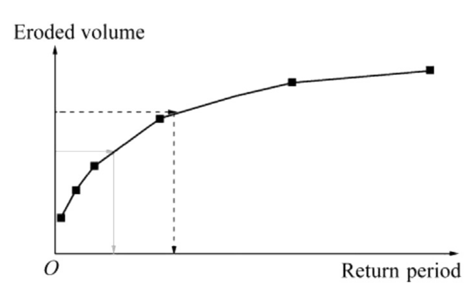

Fig. 4. Qualitative plot of eroded volume induced by single storms against their storm return periods (the arrows on the grey and dashed lines indicate two examples of the volume eroded by a storm sequence and its corresponding individual storm return period).

5. Beach recovery within storm sequences

The study approaches presented in section 4 aim to investigate beach erosion under the influence of storm sequencing without a specific focus on beach recovery within the sequences. However, to keep its full resilience against a storm sequence, beach recovery is essential as it needs to keep pace with the storm occurrence, which is often not the case (Vousdoukas et al., 2012). This makes the beach potentially more vulnerable to subsequent storms and calls for an improved understanding of beach recovery within storm sequences.

Traditionally, beach evolution during low energy conditions has received less scientific attention than beach evolution during high energy conditions, although the number of studies of post-storm recovery is increasing, with recent works describing the beach recovery processes in field conditions and numerical modelling (e.g., Scott et al., 2016; Davidson et al., 2017; Dodet et al., 2019). For example, the number of physical experiments, in which low energy wave conditions were performed, is limited (Eichentopf et al., 2018). Some of these experiments indicated that, during initial low energy wave conditions, beach profile changes associated with erosive wave conditions can continue, as also studied by Baldock et al. (2017), including continued offshore bar migration (Sánchez-Arcilla et al., 1994) and continued shoreline erosion (Sánchez-Arcilla et al., 2011). This shows that, at least in physical experiments, the description of the differences in beach profile response under high and low energy wave conditions is not straightforward. Recently, Eichentopf et al. (2018) showed that, while breaker bar characteristics (bar height and location) follow a clear evolution pattern under high energy wave conditions in large-scale experiments, bar evolution is more difficult to predict under low energy conditions. Kriebel and Dean (1993) stated that there is a temporal lag in beach response to the change in wave climate, with beach recovery being strongest at the beginning of the recovery phase. Beach recovery is generally described to occur more slowly than beach erosion (Kriebel and Dean, 1993; Castelle et al., 2007; Morales-Márquez et al., 2018).

The recovery process is often not considered in studies investigating storm sequencing. Most studies acknowledge that the beach recovers to a certain extent between successive storms but usually the beach recovery is considered small and is therefore neglected. This is particularly the case in studies where process-based numerical models are used (Splinter et al., 2014; Dissanayake et al., 2015a, 2015b). Other studies define the time interval between successive storms as such a short interval that neglecting recovery may become a reasonable assumption (Ferreira, 2005). Ferreira (2006) even defines a storm sequence as "a series of successive storms without beach recovery in between". However, despite potentially slow beach recovery, neglecting beach recovery between storms might call for further verification.

Beach recovery can be captured by different parameters. The most common parameters to quantify beach recovery are:

(1) the recovery of previously eroded sediment volumes (e.g., Birkemeier, 1979; Lee et al., 1998; Castelle et al., 2007; Vousdoukas et al., 2012; Scott et al., 2016; Biausque and Senechal, 2019);

(2) the change to a pre-defined beach state (e.g., Ranasinghe et al., 2012);

(3) the recovery of the shoreline position (e.g., Phillips et al., 2017; Angnuureng et al., 2017).

Beach recovery rates vary depending on the applied definition (as shown below) as well as on site-specific characteristics (Birkemeier, 1979; Ranasinghe et al., 2012; Dodet et al., 2019). Differences in recovery times are reflected by the maximum time intervals between successive storms to count as a storm sequence in Table 1.

One of the few studies dedicated to beach recovery within storm sequences is that by Ranasinghe et al. (2012). The beach state is used as an indicator to study nearshore morphological recovery times and its governing processes. The recovery time is obtained as the time that the nearshore morphology needs to evolve from its post-storm dissipative/longshore bar trough state to its modal state (usually transverse bar rip state at the studied sites). Beach states were defined from ARGUS imaging data from Palm Beach, Sydney, Australia (four years of data), and from Duck, North Carolina, USA (two years of data). The median of the recovery times was 11 days at Palm Beach and five days at Duck, indicating a considerable difference between sites.

The recovery times defined for Duck are apparently different from those used by Birkemeier et al. (1999), where 40 days were defined between storms to achieve full recovery (see section 3.2 and Table 1). Table 3 compares the different definitions of recovery times used by Birkemeier et al. (1999) and Ranasinghe et al. (2012). This clearly shows the subjectivity when determining recovery times and how different

Table 3
Comparison of determination of beach recovery at Duck based on Birkemeier et al. (1999) and Ranasinghe et al. (2012).

Reference	Determination of recovery time	Recovery time	Study period	Type of measurements	No. of events
Birkemeier et al. (1999)	Based on events that Lee et al. (1998) found to cause considerable shoreface volume changes	40 days	18 years (1981–1998)	Offshore wave buoy, profile measurements	10 storm sequences, 18 individual storms
Ranasinghe et al. (2012)	Based on change of nearshore morphology from its post-storm state to its most frequently occurring (modal) state	5 days (median); 7 days (mean with a standard deviation of 5 days)	2 years (1986–1988)	ARGUS video data	17 recovery events

definitions of recovery times can result in varying results even for the same site.

Ranasinghe et al. (2012) studied correlations between the recovery time and several parameters (wave height, wave power, wave period, wave steepness, breaking intensity, longshore currents, and wave direction) and found only moderate and weak correlation values which did not allow the clear determination of governing processes. In a more recent work, Angnuureng et al. (2017) investigated forcing factors for shoreline erosion and recovery. They found that, while the storm power and the previous storm conditions determine shoreline erosion during storms, for shoreline recovery the distance of the sandbar to the shoreline and tides are more important factors.

Also, Phillips et al. (2017) studied the shoreline position as an indicator for beach recovery using 10 years of data from a coastal imaging station at Narrabeen-Collaroy Beach, Australia. Shoreline recovery is defined to have ended when the shoreline is at the same position as before an initial storm. If the recovery from one storm is disrupted by a subsequent storm, shoreline recovery has only finished when the shoreline has recovered to the pre-storm position before the first storm. In line with Angnuureng et al. (2017), Phillips et al. (2017) found the proximity of the sandbar to the shoreline to be an important aspect for shoreline recovery of this particular beach, where a sandbar closer to the shoreline resulted in higher recovery rates.

It can be noted that the number of studies that have focused on beach recovery within storm sequences is very limited and that different recovery definitions result in varying recovery times. Physical processes governing beach recovery are poorly understood. As a result, most coastal numerical morphodynamic models have limited capacity to model beach recovery accurately, which is a hindrance to studying beach recovery in detail.

6. Future research needs

From the presented literature, emerging research needs in the field of storm sequences and beach evolution are identified. These main research needs are as follows:

(1) Performance of more detailed physical modelling to investigate the effects of storm sequences on beach evolution under controlled conditions. This will allow the investigation of isolated influencing factors and the acquisition of detailed temporal-spatial measurements, including bathymetric data, water surface elevations, flow velocities, and sediment concentrations.

Experiments should be performed using different chronologies of storms to study the effect of storm chronologies on beach changes. Experiments can also focus on the effect of an extreme storm within a sequence to investigate the question of whether an extreme storm generally results in the same beach profile and/or eroded volume regardless of storm chronology.

Both medium- and large-scale physical experiments will be very valuable in this endeavour, with the advantage of large-scale experiments to be less affected by scaling (Sánchez-Arcilla et al., 2011) and to use state-of-the-art instrumentation to obtain high-quality sediment concentration data (e.g., van der Zanden et al., 2015, 2016). Detailed sediment transport data allow insights into the small-scale processes that are important for beach profile evolution during storm sequences.

(2) Improvement of process-based numerical modelling capabilities to simulate beach profile evolution and hydrodynamic conditions during storm sequences. This refers especially to beach profile evolution during recovery phases, where numerical models still lack processes, especially regarding onshore sediment transport, compared to erosive wave conditions (van Rijn et al., 2011). This means that current state-of-the-art coastal morphodynamic models (e.g., XBeach) are capable of accurately reproducing storm-induced beach erosion but much work is needed to improve simulations of beach recovery during calm periods. Physical modelling with sediment transport measurements of high temporal-spatial resolution will be very useful in this endeavour as well as coordinated efforts between numerical modellers and field measurement experts.

(3) Placing similar emphasis on erosion and recovery while most previous research has primarily focused on storm-induced erosion. Beach recovery is generally more poorly understood and is often neglected when studying storm sequences. However, recovery phases are highly important for recreating beach resilience, which makes knowledge of beach recovery processes essential.

The abovementioned physical experiments would present a key tool to study different recovery conditions and to find more general descriptors of beach recovery processes. Planning of physical experiments needs to account for potentially unexpectedly long times to reach full beach recovery (Sánchez-Arcilla et al., 2011), for which also economic aspects have to be considered.

The important influencing factors for studying the beach recovery are the antecedent beach state prior to the recovery phase, the sediment availability, the wave conditions during the recovery phase and its duration, as well as the link between these factors. These aspects are certainly not easily quantified and vary between sites. In this context, a more general way of determining morphological recovery times would be desirable as these are very subjective even for the same site.

(4) More frequent and more detailed acquisition of field data of beach profile change (pre- and post-storm beach profiles) on longer timescales at sites with different conditions. This will allow detailed long-term investigations of the influence of storm sequences on beaches. Frequent, possibly event-driven, data acquisition is especially important at very dynamic sites to ensure most beach changes are captured. It is important to comprehensively study different sites with distinctly different beach characteristics, for instance the sediment type, beach slope, incident wave conditions, tidal range, and longshore effects, to improve understanding of beach evolution during storms and post-storm beach recovery.

(5) Improvement of the collaboration between coastal geomorphologists and climate scientists to better understand storm sequences and their effects on beach evolution. Climate scientists can help to understand the climate configurations

that are responsible for storm sequence generation and occurrence and to inform about the type and frequency of storm sequences that are most likely in certain regions.

7. Conclusions

The impact of storm sequences on beach morphodynamics presents an important challenge in coastal science. This research field has recently received increasing attention due to the possible increase in frequency and intensity of the most intense storms (Webster et al., 2005; Bender et al., 2010; Knutson et al., 2010).

Beaches have been recognised to respond differently to storms that occur within a sequence compared to isolated storm events. Most studies agree on that but there is no consensus on how a beach generally responds to a sequence of storms. This is not surprising considering the complexity of factors determining beach evolution under the influence of a storm sequence compared to an isolated storm. A few attempts have been made to capture beach response to storm sequences in a general way. These approaches usually focus on beach erosion during storms.

Field data investigations, numerical modelling, and the combination of the two methods present useful tools to study beach morphodynamics during storm sequences. From field studies the very site-specific characteristics regarding the definition of storm sequences, beach erosion volumes, and recovery rates become evident. Numerical models still lack accuracy, particularly under beach recovery conditions, which are usually not accounted for.

The limited number of physical experiments comprising storm sequences and the complexity of beach response under storm sequences highlight the demand for physical modelling. Investigating beach evolution under controlled conditions and obtaining detailed temporal-spatial measurements will improve the understanding of isolated factors that influence beach morphodynamics during storm sequences and support the improvement of process-based coastal numerical modelling capabilities.

Several questions on the influence of storm sequences on beach evolution have still not clearly been answered and results from different studies do not always support each other. Future research needs highlighted in this review will help to further shed light on beach evolution under storm sequence forcing.

Acknowledgements

The first author acknowledges funding from the Department of Civil and Environmental Engineering, Imperial College London, United Kingdom, and wishes to thank Dr. Ana Mijic for the valuable discussions about this review paper.

References

Angnuureng, D.B., Almar, R., Senechal, N., Castelle, B., Addo, K.A., Marieu, V., Ranasinghe, R., 2017. Shoreline resilience to individual storms and storm clusters on a meso-macrotidal barred beach. Geomorphology 290, 265–276. https://doi.org/10.1016/j.geomorph.2017.04.007.

Baldock, T.E., Birrien, F., Atkinson, A., Shimamoto, T., Wu, S., Callaghan, D.P., Nielsen, P., 2017. Morphological hysteresis in the evolution of beach profiles under sequences of wave climates, Part 1: Observations. Coast. Eng. 128, 92–105. https://doi.org/10.1016/j.coastaleng.2017.08.005.

Bender, M.A., Knutson, T.R., Tuleya, R.E., Sirutis, J.J., Vecchi, G.A., Garner, S.T., Held, I.M., 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. Science 327(5964), 454–458. https://doi.org/10.1126/science.1180568.

Biausque, M., Senechal, N., 2019. Seasonal morphological response of an open sandy beach to winter wave conditions: The example of Biscarrosse beach, SW France. Geomorphology 332, 157–169. https://doi.org/10.1016/j.geomorph.2019.02.009.

Birkemeier, W.A., 1979. The effects of the 19 December 1977 coastal storm on beaches in North Carolina and New Jersey. Shore Beach 47, 7–15.

Birkemeier, W.A., Nicholls, R.J., Lee, G., 1999. Storms, storm groups and nearshore morphological change. In: Proceedings of the Coastal Sediments. New York, pp. 1109–1122.

Cáceres, I., Grüne, J., van Rijn, L., Sánchez-Arcilla, A., Ahmari, A., Ribberink, J., 2008. Mobile-bed Tests: The SANDS project. In: Proceedings of the 31st International Conference on Coastal Engineering. Hamburg, pp. 2622–2632. https://doi.org/10.1142/9789814277426_0216.

Cáceres, I., Sánchez-Arcilla, A., 2015. Erosive and accretive mobile bed experiments in large scale tests. In: Proceedings of Coastal Sediments 2015. San Diego. https://doi.org/10.1142/9789814689977_0019.

Callaghan, D.P., Nielsen, P., Short, A., Ranasinghe, R., 2008. Statistical simulation of wave climate and extreme beach erosion. Coast. Eng. 55, 375–390. https://doi.org/10.1016/j.coastaleng.2007.12.003.

Callaghan, D.P., Roshanka, R., Short, A., 2009. Quantifying the storm erosion hazard for coastal planning. Coast. Eng. 56, 90–93. https://doi.org/10.1016/j.coastaleng.2008.10.003.

Castelle, B., Turner, I., Ruessink, B.G., Tomlinson, R.B., 2007. Impacts of storms on beach erosion: Broadbeach (Gold Coast Australia). J. Coast. Res. (SI50), 534–539.

Castelle, B., Corre, Y., Tomlinson, R., 2008. Can the Gold Coast beaches withstand extreme events? Geo. Mar. Lett. 28, 23–30. https://doi.org/10.1007/s00367-007-0086-y.

Coco, G., Senechal, N., Rejas, A., Bryan, K.R., Capo, S., Parisot, J.P., Brown, J.A., MacMahan, J.H.M., 2014. Beach response to a sequence of extreme storms. Geomorphology 204, 493–501. https://doi.org/10.1016/j.geomorph.2013.08.028.

Cox, J.C., Pirrello, M.A., 2001. Applying joint probabilities and cumulative effects to estimate storm-induced erosion and shoreline recession. Shore Beach 69(2), 5–7.

Davidson, M.A., Splinter, K.D., Turner, I.L., 2013. A simple equilibrium model for predicting shoreline change. Coast. Eng. 73, 191–202. https://doi.org/10.1016/j.coastaleng.2012.11.002.

Davidson, M.A., Turner, I.L., Splinter, K.D., Harley, M.D., 2017. Annual prediction of shoreline erosion and subsequent recovery. Coast. Eng. 130, 14–25. https://doi.org/10.1016/j.coastaleng.2017.09.008.

Dette, H.H., Larson, M., Murphy, J., Newe, J., Peters, K., Reniers, A., Steetzel, H., 2002. Application of prototype flume tests for beach nourishment assessment. Coast. Eng. 47, 137–177. https://doi.org/10.1016/S0378-3839(02)00124-2.

Dissanayake, P., Brown, J., Wisse, P., Karunarathna, H., 2015a. Effects of storm clustering on beach/dune evolution. Mar. Geol. 370, 63–75. https://doi.org/10.1016/j.margeo.2015.10.010.

Dissanayake, P., Brown, J., Wisse, P., Karunarathna, H., 2015b. Comparison of storm cluster vs isolated event impacts on beach/dune morphodynamics. Estuar. Coast Shelf Sci. 164, 301–312. https://doi.org/10.1016/j.ecss.2015.07.040.

Dissanayake, P., Brown, J., Karunarathna, H., 2015c. Impacts of storm chronology on the morphological changes of the Formby beach and dune system, UK. Nat. Hazards Earth Syst. Sci. 15, 1533–1543. https://doi.org/10.5194/nhess-15-1533-2015.

Dissanayake, P., Brown, J., Karunarathna, H., 2016. Effect of future storm clustering on beach/dune evolution and coastal flooding. In: Proceedings of the 35th Conference on Coastal Engineering. Antalya. https://doi.org/10.9753/icce.v35.sediment.19.

Dodet, G., Castelle, B., Masselink, G., Scott, T., Davidson, M., Floc'h, F., Jackson, D., 2019. Beach recovery from extreme storm activity during the 2013−14 winter along the Atlantic coast of Europe. Earth Surf. Process. Landforms 44, 393−401. https://doi.org/10.1002/esp.4500.

Dolan, R., Davis, R.E., 1992. An intensity scale for Atlantic Coast northeast storms. J. Coast. Res. 8(4), 840−853. https://doi.org/10.2307/4298040.

Dolan, R., Davis, R.E., 1994. Coastal storm hazards. J. Coast. Res. 12, 103−114.

Eichentopf, S., Cáceres, I., Alsina, J.M., 2018. Breaker bar morphodynamics under erosive and accretive wave conditions in large-scale experiments. Coast. Eng. 138, 36−48. https://doi.org/10.1016/j.coastaleng.2018.04.010.

Eichentopf, S., Baldock, T.E., Cáceres, I., Hurther, D., Karunarathna, H., Postacchini, M., Ranieri, N., van der Zanden, J., Alsina, J.M., 2019. Influence of storm sequencing and beach recovery on sediment transport and beach resilience (RESIST). In: Proceedings of the HYDRALAB$^+$ Joint User Meeting. Bucharest, pp. 247−256.

Ferreira, Ó., 2002. Prediction of the impact of storm groups and their importance in coastal evolution. In: Proceedings of the International Conference on Coastal Engineering. Cardiff. https://doi.org/2725-2730.10.1680/scc.42377.0152.

Ferreira, Ó., 2005. Storm groups versus extreme single storms: Predicted erosion and management consequences. J. Coast. Res. 42, 221−227. https://doi.org/10.2112/03-0054.1.

Ferreira, Ó., 2006. The role of storm groups in the erosion of sandy coasts. Earth Surf. Process. Landforms 31(8), 1058−1060. https://doi.org/10.1002/esp.1378.

Goda, Y., 2010. Random Seas and Design of Maritime Structures, third ed. World Scientific, Singapore. https://doi.org/10.1142/7425.

Grasso, F., Michallet, H., Barthélemy, E., Certain, R., 2009. Physical modeling of intermediate cross-shore beach morphology: Transients and equilibrium states. J. Geophys. Res.: Oceans 114(C9). https://doi.org/10.1029/2009JC005308.

Gravois, U., Baldock, T.E., Hsieh, S., Gomez, C., Callaghan, D.P., 2016. Physical modelling of the effect of storm sequences on beach profile evolution and beach erosion. In: Proceedings of the NSW Coastal Conference. Terrigal, pp. 1−13.

Harley, M., 2017. Coastal storm definition. In: Ciavola, P., Coco, G., eds., Coastal Storms: Processes and Impacts. Wiley Blackwell, Chichester, pp. 1−21. https://doi.org/10.1002/9781118937099.ch1.

Harley, M.D., Kinsela, M.A., Sánchez-García, E., Vos, K., 2019. Shoreline change mapping using crowd-sourced smartphone images. Coast. Eng. 150, 175−189. https://doi.org/10.1016/j.coastaleng.2019.04.003.

Hurst, M.D., Rood, D.H., Ellis, M.A., Anderson, R.S., Dornbusch, U., 2016. Recent acceleration in coastal cliff retreat rates on the south coast of Great Britain. Proc. Natl. Acad. Sci. U.S.A. 113(47), 13336−13341. https://doi.org/10.1073/pnas.1613044113.

Karunarathna, H., Pender, D., Ranasinghe, R., Short, A.D., Reeve, D.E., 2014a. The effects of storm clustering on beach profile variability. Mar. Geol. 348, 103−112. https://doi.org/10.1016/j.margeo.2013.12.007.

Karunarathna, H., Brown, J., Briganti, R., Pockrajac, D., Haigh, I., Beck, C., Dissanayake, P., Pedrozo-Acuna, D., Sparrow, K., Wadey, M., 2014b. Modelling memory of coastal flood systems. In: Proceedings of the 34th Conference on Coastal Engineering. Seoul. https://doi.org/10.9753/icce.v34.management.19.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K.A., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., Sugi, M., 2010. Tropical cyclones and climate change. Nat. Geosci. 3(3), 157−163. https://doi.org/10.1038/ngeo779.

Kraus, N.C., Larson, M., 1988. Beach Profile Change Measured in the Tank for Large Waves 1956−1957 and 1962. Army Engineer Waterways Experiment Station, Washington.

Kraus, N.C., McKee, S.J., Sollitt, C.K., 1994. Supertank laboratory data collection project. In: Proceedings of the 23rd International Conference on Coastal Engineering. Venice, pp. 2191−2204.

Kriebel, D.L., Dean, R.G., 1993. Convolution method for time-dependent beach-profile response. J. Waterw. Port, Coast. Ocean Eng. 119(2), 204−226. https://doi.org/10.1061/(ASCE)0733-950X(1993)119:2(204).

Kulmar, M., Lord, D., Sanderson, B., 2005. Future directions for wave data collection in New South Wales. In: Proceedings of the 17th Australasian Coastal and Ocean Engineering Conference and the 10th Australasian Port and Harbour Conference, pp. 167−172.

Kulmar, M., Modra, B., Fitzhenry, M., 2013. The New South Wales wave climate improved understanding through the introduction of directional wave monitoring buoys. In: Proceedings of the 21st Australasian Coastal and Ocean Engineering Conference and the 14th Australasian Port and Harbour Conference. Sydney.

Kuriyama, Y., Yanagishima, S., 2018. Regime shifts in the multi-annual evolution of a sandy beach profile. Earth Surf. Process. Landforms 43, 3133−3141. https://doi.org/10.1002/esp.4475.

Lee, G.-H., Nicholls, R.J., Birkemeier, W.A., 1998. Storm-driven variability of the beach-nearshore profile at Duck, North California, USA, 1981−1991. Mar. Geol. 148(3−4), 163−177. https://doi.org/10.1016/S0025-3227(98)00010-3.

Lord, D., Kulmar, M., 2000. The 1974 storms revisited: 25 years experience in ocean wave measurement along the south-east Australian Coast. In: Proceedings of the 27th International Conference on Coastal Engineering, pp. 559−572. https://doi.org/10.1061/40549(276)44.

Loureiro, C., Ferreira, Ó., Cooper, J.A.G., 2012. Extreme erosion on high-energy embayed beaches: Influence of megarips and storm grouping. Geomorphology 139−140, 155−171. https://doi.org/10.1016/j.geomorph.2011.10.013.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., Aarninkhof, S., 2018. The state of the world's beaches. Sci. Rep. 8, 1−11. https://doi.org/10.1038/s41598-018-24630-6.

Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M., Conley, D., 2016a. The extreme 2013/2014 winter storms: Hydrodynamic forcing and coastal response along the southwest coast of England. Earth Surf. Process. Landforms 41, 378−391. https://doi.org/10.1002/esp.3836.

Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson, D., Floc'h, F., 2016b. Extreme wave activity during 2013/14 winter and morphological impacts along the Atlantic coast of Europe. Geophys. Res. Lett. 2135−2143. https://doi.org/10.1002/2015GL067492.

Masselink, G., Ruju, A., Conley, D., Turner, I., Ruessink, G., Matias, A., Thompson, C., Castelle, B., Puleo, J., Citerone, V., Wolters, G., 2016c. Large-scale barrier dynamics experiment II (BARDEX II): Experimental design, instrumentation, test program, and data set. Coast. Eng. 113, 3−18. https://doi.org/10.1016/j.coastaleng.2015.07.009.

Miller, J.K., Dean, R.G., 2004. A simple new shoreline change model. Coast. Eng. 51, 531−556. https://doi.org/10.1016/j.coastaleng.2004.05.006.

Morales-Márquez, V., Orfila, A., Simarro, G., Gómez-Pujol, L., Álvarez-Ellacuría, A., Conti, D., Galán, A., Osorio, A.F., Marcos, M., 2018. Numerical and remote techniques for operational beach management under storm group forcing. Nat. Hazards Earth Syst. Sci. 18, 3211−3223. https://doi.org/10.5194/nhess-18-3211-2018.

Mortlock, T.R., Goodwin, I.D., McAneney, J.K., Roche, K., 2017. The June 2016 Australian East Coast Low: Importance of wave direction for coastal erosion assessment. Water 9(2), 1−22. https://doi.org/10.3390/w9020121.

Morton, R.A., 1976. Effects of Hurricane Eloise on beach and coastal structures, Florida Panhandle. Geology 277−280. https://doi.org/10.1130/0091-7613(1976)4<277:EOHEOB>2.0.CO;2.

Morton, R.A., Gibeaut, J.C., Paine, J.G., 1995. Meso-scale transfer of sand during and after storms: Implications for prediction of shoreline movement. Mar. Geol. 126(1−4), 161−179. https://doi.org/10.1016/0025-3227(95)00071-6.

Morton, R.A., 2002. Factors controlling storm impacts on coastal barriers and beaches: A preliminary basis for near real-time forecasting. J. Coast. Res. 18(3), 486−501. https://doi.org/10.2307/4299096.

Nichol, S., McPherson, A., Floyd, H., Jiang, W., Davies, G., Moore, D., Owens, K., Sexton, J., Baldock, T.E., Callaghan, D.P., Gravois, U., 2016. Resilience to Clustered Disaster Events at the Coast: Storm Surge. Annual Project Report. Canberra.

Nott, J., Hayne, M., 2001. High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. Nature 413, 508−512. https://doi.org/10.1038/35097055.

Pender, D., Karunarathna, H., 2013. A statistical-process based approach for modelling beach profile variability. Coast. Eng. 81, 19−29. https://doi.org/10.1016/j.coastaleng.2013.06.006.

Phillips, M.S., Harley, M.D., Turner, I.L., Splinter, K.D., Cox, R.J., 2017. Shoreline recovery on wave-dominated sandy coastlines: The role of sandbar morphodynamics and nearshore wave parameters. Mar. Geol. 385, 146−159. https://doi.org/10.1016/j.margeo.2017.01.005.

Phillips, M.S., Blenkinsopp, C.E., Splinter, K.D., Harley, M.D., Turner, I.L., 2019. Modes of berm and beachface recovery following storm reset: Observations using a continuously scanning lidar. J. Geophys. Res.: Earth Surf. 124, 720−736. https://doi.org/10.1029/2018JF004895.

Ranasinghe, R., Holman, R., de Schipper, M., Lippmann, T., Wehof, J., Duong, T.M., Roelvink, D., Stive, M., 2012. Quantifying nearshore morphological recovery time scales using argus video imaging: Palm Beach, Sydney and Duck, North Carolina. In: Proceedings of the 33rd International Conference on Coastal Engineering. Santander. https://doi.org/10.9753/icce.v33.sediment.24.

Reguero, B.J., Losada, I.J., Méndez, F.J., 2019. A recent increase in global wave power as a consequence of oceanic warming. Nat. Commun. 10(205), 1−14. https://doi.org/10.1038/s41467-018-08066-0.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133−1152. https://doi.org/10.1016/j.coastaleng.2009.08.006.

Sánchez-Arcilla, A., Roelvink, J.A., O'Connor, B.A., Reniers, A., Jiménez, J.A., 1994. The Delta Flume'93 experiment. Coast. Dyn. 94, 488−502.

Sánchez-Arcilla, A., Cáceres, I., van Rijn, L., Grüne, J., 2011. Revisiting mobile bed tests for beach profile dynamics. Coast. Eng. 58, 583−593. https://doi.org/10.1016/j.coastaleng.2011.01.005.

Scott, T., Masselink, G., O'Hare, T., Saulter, A., Poate, T., Russell, P., Davidson, M., Conley, D., 2016. The extreme 2013/2014 winter storms: Beach recovery along the southwest coast of England. Mar. Geol. 382, 224−241. https://doi.org/10.1016/j.margeo.2016.10.011.

Sénéchal, N., Castelle, B., Bryan, K.R., 2017. Storm clustering and beach response. In: Ciavola, P., Coco, G., eds., Coastal Storms: Processes and Impacts. Wiley Blackwell, Chichester, pp. 151−174. https://doi.org/10.1002/9781118937099.ch8.

Shimizu, T., Ikeno, M., 1996. Experimental study on sediment transport in surf and swash zones using large wave flume. In: Proceedings of the 25th Conference on Coastal Engineering. Orlando, pp. 3076−3089. https://doi.org/10.9753/icce.v25.%25p.

Splinter, K.D., Carley, J.T., Golshani, A., Tomlinson, R., 2014. A relationship to describe the cumulative impact of storm clusters on beach erosion. Coast. Eng. 83, 49−55. https://doi.org/10.1016/j.coastaleng.2013.10.001.

Thom, B.G., Bowman, C.M., 1980. Beach erosion-accretion at two time scales. In: Proceedings of the 17th International Conference on Coastal Engineering. Sydney, pp. 934−945. https://doi.org/10.9753/icce.v17.57.

van der Zanden, J., Alsina, J.M., Cáceres, I., Buijsrogge, R.H., Ribberink, J.S., 2015. Bed level motions and sheet flow processes in the swash zone: Observations with a new conductivity-based concentration measuring technique (CCM+). Coast. Eng. 105, 47−65. https://doi.org/10.1016/j.coastaleng.2015.08.009.

van der Zanden, J., van der A, D.A., Hurther, D., Cáceres, I., O'Donoghue, T., Ribberink, J.S., 2016. Near-bed hydrodynamics and turbulence below a large-scale plunging breaking wave over a mobile barred bed profile. J. Geophys. Res.: Oceans 121(8), 6482−6506. https://doi.org/10.1002/2016JC011909.

van Enckevort, I.M.J., Ruessink, B.G., 2003. Video observations of nearshore bar behaviour, Part 1: Alongshore uniform variability. Cont. Shelf Res. 23, 501−512. https://doi.org/10.1016/S0278-4343(02)00234-0.

van Rijn, L.C., Walstra, D.J.R., Grasmeijer, B., Sutherland, J., Pan, S., Sierra, J.P., 2003. The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based profile models. Coast. Eng. 47, 295−327. https://doi.org/10.1016/S0378-3839(02)00120-5.

van Rijn, L.C., Tonnon, P.K., Walstra, D.J.R., 2011. Numerical modelling of erosion and accretion of plane sloping beaches at different scales. Coast. Eng. 58, 637−655. https://doi.org/10.1016/j.coastaleng.2011.01.009.

Vos, K., Harley, M.D., Splinter, K.D., Simmons, J.A., Turner, I.L., 2019. Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. Coast. Eng. 150, 160−174. https://doi.org/10.1016/j.coastaleng.2019.04.004.

Vousdoukas, M.I., Almeida, L.P.M., Ferreira, Ó., 2012. Beach erosion and recovery during consecutive storms at a steep-sloping, meso-tidal beach. Earth Surf. Process. Landforms 37, 583−593. https://doi.org/10.1002/esp.2264.

Webster, P.J., Holland, G.J., Curray, J.A., Chang, H.-R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309, 1844−1846. https://doi.org/10.1111/j.0033-0124.1951.006_a.x.

Williams, J., Masselink, G., Buscombe, D., Turner, I., Matias, A., Ferreira, O., Bradbury, A., Metje, N., Coates, L., Chapman, D., et al., 2009. BARDEX (barrier dynamics experiment): Taking the beach into the laboratory. J. Coast. Res. (SI56), 158−162.

Williams, J.J., Buscombe, D., Masselink, G., Turner, I.L., Swinkels, C., 2012. Barrier dynamics experiment (BARDEX): Aims, design and procedures. Coast. Eng. 63, 3−12. https://doi.org/10.1016/j.coastaleng.2011.12.009.

Woodroffe, C., Cowel, P., Callaghan, D., Ranasinghe, R., Jongejan, R., Wainwright, D., Barry, S., Rogers, K., Dougherty, A., 2012. Approaches to Risk Assessment on Australian Coasts: A Model Framework for Assessing Risk and Adaptation to Climate Change on Australian Coasts. National Climate Change Adaptation Research Facility, Gold Coast.

Yates, M.L., Guza, R.T., O'Reilly, W.C., 2009. Equilibrium shoreline response: Observations and modeling. J. Geophys. Res.: Oceans 114, C09014. https://doi.org/10.1029/2009JC005359.

Yoon, H.D., Cox, D.T., 2010. Large-scale laboratory observations of wave breaking turbulence over an evolving beach. J. Geophys. Res.: Oceans 115(C10). https://doi.org/10.1029/2009JC005748.

You, Z., Lord, D., 2008. Influence of the El Niño-Southern Oscillation on NSW coastal storm severity. J. Coast. Res. 2(sp2), 203−207. https://doi.org/10.2112/06-0690.1.